

Constraints on W Prime Models for the $t\bar{t}$ Asymmetry

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This note is a synopsis of a talk given at the SUSY 2011 conference at Fermilab on September 1, 2011. We discuss if the Tevatron $t\bar{t}$ asymmetry can be explained by T-channel exchange of a W' gauge boson coupling to down and top quarks. In a spontaneously broken gauge theory, such a W' is necessarily accompanied by a Z' at a similar mass scale. Null results from Tevatron searches for dijet and dilepton resonances imply large mass splitting between the W' and Z' . We argue that such splitting can only be accomplished if the gauge symmetry is broken by a scalar in a large dimension representation of the gauge group, for which no perturbative description exists.

I. INTRODUCTION

Experiments at the Tevatron have observed a forward-backward asymmetry in $t\bar{t}$ pair production exceeding the NLO QCD prediction of 0.06 ± 0.01 [1–4]. The CDF collaboration found that the asymmetry is especially pronounced in the high invariant mass bin with $M_{t\bar{t}} \geq 450$ GeV. In this bin asymmetries of 0.475 ± 0.114 and 0.212 ± 0.096 were measured in the semileptonic [5] and dileptonic modes [6], respectively. The Standard Model prediction as obtained with the MCFM code is 0.088 ± 0.013 .

Taking into account the total $p\bar{p} \rightarrow t\bar{t}$ cross section and event reconstruction efficiencies, it was found in [7] that T-channel exchange of flavor-changing Z' and W' bosons can produce a sufficient asymmetry while fulfilling all experimental constraints. However, flavor-changing Z' exchange implies the production of same-sign top pairs at hadron colliders, which faces strong limits from the Tevatron and the LHC [8–11]. One solution to the same sign top production problem has been proposed in [12] by embedding a Z' with couplings to up and top quarks in a non-Abelian flavor symmetry. It was found that all experimental constraints can be avoided if the Z' couplings are nearly diagonal in the mass eigenstate basis. In this talk we address the question if a similar gauge theory with a W' coupling to down and top quarks can explain the observed $t\bar{t}$ asymmetry.

II. GAUGE SYMMETRY CONSTRAINTS ON W' MODELS

A. Mixing with Hypercharge

Explaining the Tevatron $t\bar{t}$ asymmetry with T -channel exchange of a W' boson requires that down and top quarks transform into each other under the

action of a non-Abelian symmetry group. Because of $SU(2)_L$ gauge invariance, this rotation can not involve left-handed fields.

The minimal realization of this symmetry is therefore $SU(2)_R$, under which the right-handed quark fields transform as a doublet. Since the electric charges of the down and top quark differ by one unit, this new symmetry can not be added to the Standard Model as an independent $SU(2)$ factor. The simplest symmetry breaking structure

$$SU(2)_R \rightarrow U(1)_Y$$

produces two charged W' bosons, but incorrectly predicts hypercharges of $\pm 1/2$ for t^c and d^c . An additional $U(1)$ factor

$$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$$

is therefore required, implying the existence of a neutral Z' boson. This Z' has flavor-diagonal couplings and does not contribute to the Tevatron $t\bar{t}$ asymmetry or to same-sign top production at the Tevatron and the LHC. Experimental limits on the Z' originate from searches for dijet and $t\bar{t}$ resonances and the search for its suppressed dileptonic decay modes.

To reproduce the $t\bar{t}$ asymmetry, the W' coupling constant g_R is required to be large compared to the standard model hypercharge coupling g' . The relation

$$\frac{1}{g'^2} = \frac{1}{g_R^2} + \frac{1}{g_X^2} \quad (1)$$

then implies $g_X \approx g'$ and therefore small mixing between $SU(2)_R$ and $U(1)_X$. If the symmetry is broken by the VEV of a scalar doublet as in the Standard Model, the Z' is approximately degenerate with the W' .

TABLE I. $SU(2)_R$ and $U(1)_X$ charges of Standard Model fermions in the minimal W' model.

field	X	T_R^3
t_R	$1/6$	$+1/2$
d_R	$1/6$	$-1/2$
others	Y	0

B. Couplings to Fermions

In the limit of zero neutral gauge boson mixing, the W' and Z' couplings are

$$\begin{aligned} \mathcal{L}_{\text{int}} &\supset \left(\bar{t} \ d \right) \gamma^\mu \left[\partial_\mu - ig \frac{\sigma_a}{2} W_{R\mu}^a \right] P_R \begin{pmatrix} t \\ d \end{pmatrix} \\ &\supset -ig \frac{1}{\sqrt{2}} \bar{t} \gamma_\mu P_R d W_{R\mu}^+ - ig \frac{1}{\sqrt{2}} \bar{d} \gamma_\mu P_R t W_{R\mu}^- \\ &\quad - ig \frac{1}{2} (\bar{t} \gamma_\mu P_R t - \bar{d} \gamma_\mu P_R d) W_{R\mu}^3 \end{aligned} \quad (2)$$

In this limit, the $Z' = W_R^3$ couples only to $d\bar{d}$ and $t\bar{t}$.

As the W' coupling is however finite, some degree of mixing with the hypercharge $U(1)_X$ is unavoidable and indeed necessary to obtain a charged gauge boson. To calculate the branching fraction due to hypercharge admixture, let us first note that the gauge boson mixing matrix is

$$\begin{pmatrix} Z' \\ B \end{pmatrix} = \begin{pmatrix} \cos \theta_R & -\sin \theta_R \\ \sin \theta_R & \cos \theta_R \end{pmatrix} \begin{pmatrix} W_R^3 \\ X \end{pmatrix}, \quad (3)$$

where X is the $U(1)_X$ hypercharge gauge boson and

$$\sin \theta_R = \frac{g_X}{\sqrt{g_X^2 + g_R^2}}, \quad \cos \theta_R = \frac{g_R}{\sqrt{g_X^2 + g_R^2}}. \quad (4)$$

The fermion Z' current is then

$$J_{Z'}^\mu(f) = \sum_f (g_R \cos \theta_R T_R^3 - g_X \sin \theta_R X) f^\dagger \bar{\sigma}^\mu f. \quad (5)$$

with fermion charges as listed in Table I.

In the general case of non-zero left-handed and right-handed couplings

$$\mathcal{L}_{\text{int}} \supset \sum_f i \bar{f} \gamma_\mu (k_R P_R + k_L P_L) f Z'^\mu, \quad (6)$$

the partial decay width of the Z' into any type of

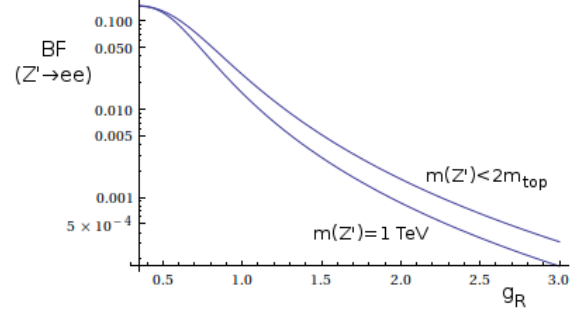


FIG. 1. $Z' \rightarrow e^+ e^-$ branching fraction as a function of g_R in the tree level approximation. All fermion masses except m_{top} are assumed to be zero.

fermion pairs is

$$\begin{aligned} \Gamma(Z' \rightarrow f\bar{f}) &= \frac{N_C}{24\pi} M_{Z'} \sqrt{1 - 4\zeta^2} \\ &\times [(k_L^2 + k_R^2)(1 - \zeta^2) + 6\zeta^2 k_L k_R], \end{aligned} \quad (7)$$

where $\zeta = m_f/M_{Z'}$. In the interesting region of large W' coupling, the Z' is mostly the neutral $SU(2)_R$ gauge boson with only small hypercharge admixture. The small mixing angle suppresses the branching fraction to leptons by

$$\frac{\Gamma(Z' \rightarrow e^+ e^-)}{\Gamma(Z' \rightarrow d\bar{d})} \approx \frac{1}{N_c} \frac{g_X^2 \sin^2 \theta_R}{g_R^2 \cos^2 \theta_R} = \frac{1}{3} \left(\frac{g_X}{g_R} \right)^4. \quad (8)$$

Generating a sufficient asymmetry requires $g_R \gtrsim 1$, such that $g_X = g' \approx 1/3$. The leptonic decay modes of the Z' are then suppressed by more than two orders of magnitude compared to the hadronic modes (see Fig.1).

C. Embedding into Left-Right Model

Coupling the W' only to right-handed down and top quarks is sufficient to generate a $t\bar{t}$ forward-backward asymmetry at the Tevatron. A possible objection to this construction is the ad-hoc flavor structure. We therefore briefly note that it is possible to embed the above theory into a left-right model with maximal mixing between the first and third family of right-handed quarks and asymmetric couplings to left and righthanded gauge bosons. The strong constraints from kaon mixing on the mass of the W' boson [13, 14] can be avoided by fine-tuning the right-handed analog of the CKM matrix to the

off-diagonal unitary form

$$V^R = (U_u^R)^\dagger U_d^R = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad (9)$$

in the mass basis, up to small additional mixing between the families.

III. TEVATRON RESONANCE SEARCHES

At hadron colliders, the Z' is produced as a resonance from a $d\bar{d}$ initial state. The Z' is therefore constrained by searches for dijet resonances [15] and top pair production resonances [16].

Leptonic decays of the Z' add additional constraints on the model. As noted above, the decay width to leptons is due to hypercharge admixture and suppressed by the small mixing angle. However, the limits on $p\bar{p} \rightarrow Z' \rightarrow e^+e^-$ from Tevatron searches are in the femtobarn range [17] and therefore severely restrict the model parameter space. They become especially relevant for small Z' mass (i.e. large production cross section) and large $U(1)_X$ coupling constant, i.e. large mixing and therefore large branching fraction to dileptons.

Assembling constraints from Tevatron $Z' \rightarrow$ dijet, $t\bar{t}$ and e^+e^- searches, we find that the dielectron search is complimentary to the search for hadronic decays at small Z' mass. The $SU(2)_R$ model Z' is therefore excluded for all couplings up to 700 GeV (Fig.2). At the corresponding $SU(2)_R$ coupling of $g_R = 1.4$, the Z' mass has to be as light as 200 GeV to produce a sufficient $t\bar{t}$ asymmetry.

If the W' originates from a left-right model as described above, all six quark flavors are charged under $SU(2)_R$. The branching fraction to leptons at large g_R is then reduced by a factor of 1/3. However, the conclusions from Tevatron dilepton searches are virtually unchanged because of the additional $u\bar{u} \rightarrow Z'$ production channel.

A light W' with couplings to leptons is strongly excluded by $W' \rightarrow \ell + X$ searches. Such a universally coupling W'_R at the TeV scale mass is however an attractive search target for the LHC [18].

IV. LARGE HIGGS REPRESENTATIONS

Explaining the Tevatron asymmetry with a W' requires splitting the mass of the Z' and W' bosons by at least a factor of three. Since the mixing angle

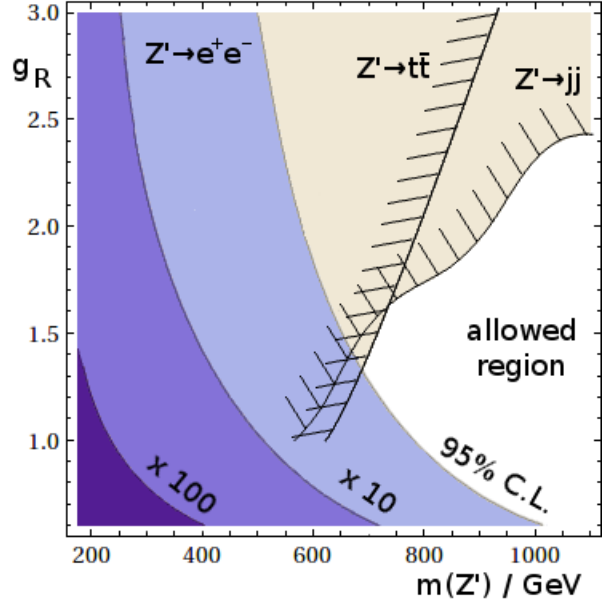


FIG. 2. Tevatron constraints on the simplified $SU(2)_R$ model in Z' mass vs. $SU(2)_R$ coupling parameter space. The shaded contours show the 95 % C.L. on $\sigma(p\bar{p} \rightarrow Z' \rightarrow e^+e^-)$ from Tevatron dielectron resonance searches as well as 10 and 100 times the excluded cross section \times branching fraction.

between the hypercharge and $SU(2)_R$ gauge groups must be small, the only way this can be accomplished is with a scalar VEV in a large representation of $SU(2)_R$. In the following section we will briefly outline why such a symmetry breaking setup is disfavored by theoretical arguments.

Let us assume that the right-handed gauge symmetry is broken by a VEV in the lowest weight component of a scalar Φ_N transforming in the complex, dimension N (i.e. isospin $s = (N - 1)/2$) representation of $SU(2)_R$. Neglecting the small mixing with hypercharge, the gauge boson masses are

$$M_{Z'} = \frac{gf}{2} (N - 1), \quad M_{W'} = \frac{gf}{2} \sqrt{N - 1}. \quad (10)$$

Additionally, a doublet Higgs Φ_2 is required to generate masses for the top and down quarks. Ignoring this for the moment, we can ask what size of the Higgs representation is necessary to reconcile the Tevatron $Z' \rightarrow jj$, $Z' \rightarrow t\bar{t}$ and $Z' \rightarrow e^+e^-$ constraints with the asymmetry from T-channel W' exchange. Not overproducing $t\bar{t}$ at large invariant mass while generating a sufficient asymmetry requires a W' with a mass $m_{W'} = 200$ GeV and a coupling $g_R = 1.4$. Since the Z' is excluded by dijet

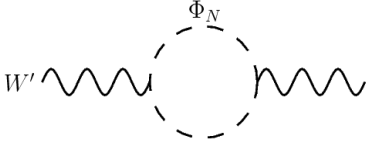


FIG. 3. Scalar loop contribution to the W' and Z' gauge boson propagators.

constraints up to 700 GeV, we find

$$\sqrt{D-1} > \frac{700 \text{ GeV}}{200 \text{ GeV}} \Rightarrow D \geq 14. \quad (11)$$

The VEV of the doublet Φ_2 contributes equally to the W' and Z' masses and requires the dimension of Φ_N to be even larger than estimated above.

Φ_N is charged under the $SU(2)_R$ gauge group and therefore contributes to the gauge boson propagator (Fig. 3) with strength

$$\sim \frac{g_R^2}{16\pi^2} \frac{\text{Tr}(T_D^a T_D^a)}{\text{Tr} \square} = \frac{g_R^2}{16\pi^2} \frac{1}{12} (D^3 - D). \quad (12)$$

For $D \geq 13$ and $g_R = 1$, the scalar loop contribution to the gauge boson propagator is comparable to the tree level term, implying the breakdown of perturbativity and the loss of predictive power of the theory.

V. CONCLUSIONS

By combining gauge symmetry arguments and negative Tevatron Z' resonance search results, we

conclude that the Tevatron $t\bar{t}$ asymmetry can not be explained by T-channel exchange of a weakly coupled W' gauge boson.

Unitarity bounds on partial wave $VV \rightarrow VV$ and $Vf \rightarrow Vf$ scattering amplitudes require any theory of massive vector bosons to be either equivalent to a spontaneously broken gauge theory or result from strongly coupled new physics [19]. The momentum scale at which new states are needed to unitarize scattering amplitudes can be estimated by

$$\frac{s}{4M_{W'}^2} = \left(\frac{g^2}{4\pi} \right)^{-1}. \quad (13)$$

Generating a sufficiently large asymmetry requires $m_{W'} = 200 \text{ GeV}$ and $g_R \approx 1$, implying $\sqrt{s} \approx 1 \text{ TeV}$. The absence of additional operators generated by strong dynamics can then not be explained except by fine tuning.¹

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¹ This line of argument is developed further in the recently published article [20].

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